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LUMINOSITY REQUIREMENTS FOR HIGGS RESONANCE STUDIES AT THE FIRST MUON COLLIDER*

Zohreh Parsa
Department of Physics
Brookhaven National Laboratory
Upton, NY 11973

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Luminosity Requirement for Higgs Resonance studies At The First Muon Collider*

Zohreh Parsa

Physics Department, Brookhaven National Laboratory, Upton, New York 11973

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Abstract. The results of our Higgs resonance studies at the first Muon collider for the on-resonance goal of $\mathcal{L}_{\rm ave} \simeq 5 \times 10^{30}{\rm cm}^{-2}$ and $\mathcal{L}_{\rm ave} \simeq 5 \times 10^{31}{\rm cm}^{-2}$ is given. Our analysis indicates that $\mathcal{L}_{\rm ave} \simeq 5 \times 10^{30}{\rm cm}^{-2}$ is too low and at least an additional order of magnitude increase in luminosity is needed. We investigated [4,7] the effect of beam polarization on Higgs resonance signals and backgrounds ($b\bar{b}$, $\tau\bar{\tau}$, $c\bar{c}$), angular distributions (forward-backward charge asymmetries) and the resulting effective enhancement of the Higgs signal relative to the background, as well as the reduction in scan time required for Higgs "discovery".

- If the Higgs boson has a mass $\lesssim 160$ GeV (i.e. below the W^+W^- decay threshold), it will have a very narrow width and can be resonantly studied in the s-channel via $\mu^-\mu^+ \rightarrow H$ production at the First Muon Collider (FMC) [1,2]. A strategy for "light" Higgs physics studies would be to first find the Higgs particle at LEPII, the Tevatron, or the LHC and then thoroughly scrutinize

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its properties on resonance at the FMC. There, one would hope to precisely determine the Higgs mass, width, and primary decay rates [3].

- The FMC Higgs resonance program would entail two stages: 1) "Discovery" via an energy scan which pinpoints the precise resonance position and (perhaps) determines its width. Since pre-FMC efforts may only determine the Higgs mass to $\sim \pm 0.2$–1 GeV and its width is expected to be narrow $\mathcal{O}(1\sim 30 \text{ MeV})$ for $m_H \lesssim 160$ GeV, the resonance scan may be very time consuming [3]. 2) Precision measurements of the primary Higgs decay modes. Deviations from standard model expectations could point to additional Higgs structure or elucidate the framework of supersymmetry [3].
- The Higgs resonance "discovery" capability and scan time will depend on $N_S/\sqrt{N_B}$ (the scan time is proportional to N_B/N_S^2), where N_S is the Higgs signal and N_B is the expected background. The precision measurement sensitivity will be determined by $N_S/\sqrt{N_B + N_S}$. For both, it will be extremely important to enhance the signal and suppress backgrounds as much as possible. To that end, one should employ highly resolved $\mu^+\mu^-$ beams with a very small energy spread. The proposed $\Delta E/E \simeq 3 \times 10^{-5}$ is well matched to the narrow Higgs width. It allows $N_S/N_B \sim \mathcal{O}(1)$ for the primary $H \to b\bar{b}$ mode (see Table 1 and 2). Unfortunately, high resolution is accompanied by luminosity loss. The original on-resonance goal of $\mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ is too low. Hence, we have assumed in Table 2 and throughout this paper that an additional order of magnitude increase in luminosity to $5\times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ is attainable while maintaining outstanding beam resolution.
- For example, a factor of 10 increase in Luminosity (Table 2) reduces the running (scan) time by factor 10 less. Thus instead of a "3 year" running time, it will be reduced to ($\frac{3}{10}$ year) over "3 months".

- Expectations for $m_H = 110$ GeV are illustrated in Table 1 for luminosity $\mathcal{L}_{\text{ave}} \simeq 5 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$ and in Table 2 for luminosity $\mathcal{L}_{\text{ave}} \simeq 5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$.

TABLE 1. Expected signals and backgrounds (fully integrated) for a standard model Higgs with $m_H = 110$ GeV, $\Gamma_H \simeq 3$ MeV. Muon collider resonance conditions with no polarization, $\Delta E/E \simeq 3 \times 10^{-5}$, and $L = 0.05$ fb^{-1} are assumed. The total number of Higgs scalars produced is ~ 3000. Realistic efficiency and acceptance cuts are likely to dilute signal and backgrounds for $b\bar{b}$ and $c\bar{c}$ by a 0.5 factor.

$H \rightarrow$	$b\bar{b}$	$c\bar{c}$	$\tau\bar{\tau}$
N_S (events)	2400	120	270
N_B (events)	2520	2416	945
$\pm\sqrt{N_S + N_B}/N_S$	±0.03	±0.42	±0.13

TABLE 2. Expected signals and backgrounds (fully integrated) for a standard model Higgs with $m_H = 110$ GeV, $\Gamma_H \simeq 3$ MeV. Muon collider resonance conditions with no polarization, $\Delta E/E \simeq 3 \times 10^{-5}$, and $L = 0.5$ fb^{-1} are assumed. The total number of Higgs scalars produced is $\sim 30,000$. Realistic efficiency and acceptance cuts are likely to dilute signal and backgrounds for $b\bar{b}$ and $c\bar{c}$ by a 0.5 factor.

$H \rightarrow$	$b\bar{b}$	$c\bar{c}$	$\tau\bar{\tau}$
N_S (events)	$24,000$	$1,200$	$2,700$
N_B (events)	$25,200$	$24,160$	$9,450$
$\pm\sqrt{N_S + N_B}/N_S$	±0.009	±0.13	±0.04

- In these tables $c\bar{c}$ branching ratios have been reduced compared to those given previously [4,7]. The values given here assume smaller charm quark mass. The prediction is quite sensitive to the mass value assumed.

  The selection of the energy and luminosity depends on 1) the reduced scan time to normal time needed, and 2) to improve precision to do physics. For example, to measure $c\bar{c}$, a factor of 10 increase in luminosity results in the improvement from 42%,

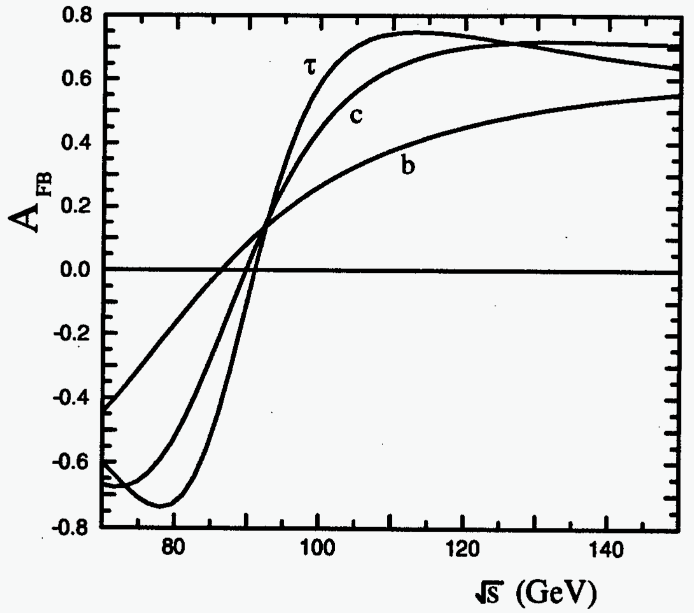

FIGURE 1. Forward-backward asymmetry for $\mu^-\mu^+ \rightarrow f\bar{f}$.

(Table 1) to about 13% (Table 2).

Other decays such as WW^* and ZZ^* are very small for this mass regions and to measure them need to improve precision. The parameter $\pm\sqrt{N_S + N_B}/N_S$ in Tables 1 and 2 was included for convenient. Further note, the values listed in Tables 1 and 2 should be reduced by $\frac{1}{\sqrt{2}}$ to include the effect of acceptance.

- Here we describe additional ways of potentially enhancing the Higgs signal to background ratio. The Higgs signal $\mu^-\mu^+ \rightarrow H \rightarrow f\bar{f}$ results from left-left (LL) or right-right (RR) beam polarizations and leads to an isotropic (i.e. constant) $f\bar{f}$ signal in $\cos\theta$ (the angle between the μ^- and f). Standard model backgrounds $\mu^-\mu^+ \rightarrow \gamma^*$ or $Z^* \rightarrow f\bar{f}$ result from LR or RL initial state polarizations and give rise to $(1 + \cos^2\theta + \frac{8}{3}A_{FB}\cos\theta)$ angular distributions. Similar statements apply to WW^* and ZZ^* final states, but those modes will not be discussed here.

- To illustrate the difference between signal, $\mu^-\mu^+ \rightarrow H \rightarrow f\bar{f}$, and background, $\mu^-\mu^+ \to \gamma^*$ or $Z^* \to f\bar{f}$, we give the combined differential production rate with respect to $x \equiv \cos\theta = 4\mathbf{p}_{\mu^-}\cdot\mathbf{p}_{\mathbf{f}}/s$ for polarized muon beams and fixed luminosity

$$\begin{aligned}\frac{dN(\mu^-\mu^+ \to f\bar{f})}{dx} &= \frac{1}{2}N_S(1+P_+P_-) \qquad (1)\\ &+ \frac{3}{8}N_B[1-P_+P_- + (P_+-P_-)A_{LR}](1+x^2+\frac{8}{3}xA_{eff}).\end{aligned}$$

$P_+(P_-)$ is the $\mu^+(\mu^-)$ polarization with $P=-1$ pure left-handed, $P=+1$ pure right handed, and $P=0$ unpolarized. N_S is the fully integrated $(-1 < x \leq 1)$ Higgs signal and N_B the integrated background for the case of unpolarized beams, $P_+ = P_- = 0$. In that general expression,

$$A_{LR} \equiv \frac{\sigma_{LR\to LR}+\sigma_{LR\to RL}-\sigma_{RL\to RL}-\sigma_{RL\to LR}}{\sigma_{LR\to LR}+\sigma_{LR\to RL}+\sigma_{RL\to RL}+\sigma_{RL\to LR}}, \qquad (2)$$

where, for example, $LR \to LR$ stands for $\mu_L^-\mu_R^+ \to f_L\bar{f}_R$. The effective forward-backward asymmetry is given by

$$A_{eff} = \frac{A_{FB}+P_{eff}A_{LR}^{FB}}{1+P_{eff}A_{LR}}, \qquad (3)$$

with

$$P_{eff} = \frac{P_+-P_-}{1-P_+P_-}, \qquad (4)$$

$$A_{FB} = \frac{3}{4}\frac{\sigma_{LR\to LR}+\sigma_{RL\to RL}-\sigma_{LR\to RL}-\sigma_{RL\to LR}}{\sigma_{LR\to LR}+\sigma_{RL\to RL}+\sigma_{LR\to RL}+\sigma_{RL\to LR}}, \qquad (5)$$

$$A_{LR}^{FB} = \frac{3}{4}\frac{\sigma_{LR\to LR}+\sigma_{RL\to LR}-\sigma_{LR\to RL}-\sigma_{RL\to RL}}{\sigma_{LR\to LR}+\sigma_{RL\to LR}+\sigma_{LR\to RL}+\sigma_{RL\to RL}}. \qquad (6)$$

and the $\mu_i^-\mu_j^+ \to f_{i'}\bar{f}_{j'}$, cross sections $(i \neq j)$ are to lowest order

$$\begin{aligned}\sigma_{ij\to i'j'} &= (N_C)\sigma_0\left[1-\frac{s}{m_Z^2}\left(1+\frac{(T_{3\mu_i}-Q_\mu\sin^2\theta_W)(T_{3f_{i'}}-Q_f\sin^2\theta_W)}{Q_\mu Q_f\sin^2\theta_W\cos^2\theta_W}\right)\right]^2,\\ T_{3\mu_L} &= T_{3\tau_L} = T_{3b_L} = -T_{3c_L} = -1/2, \qquad (7)\\ T_{3f_R} &= 0, \quad Q_\mu = Q_\tau = 3Q_b = -\frac{3}{2}Q_c = -1 \qquad (N_C = 3 \text{ for } f = b, c).\end{aligned}$$

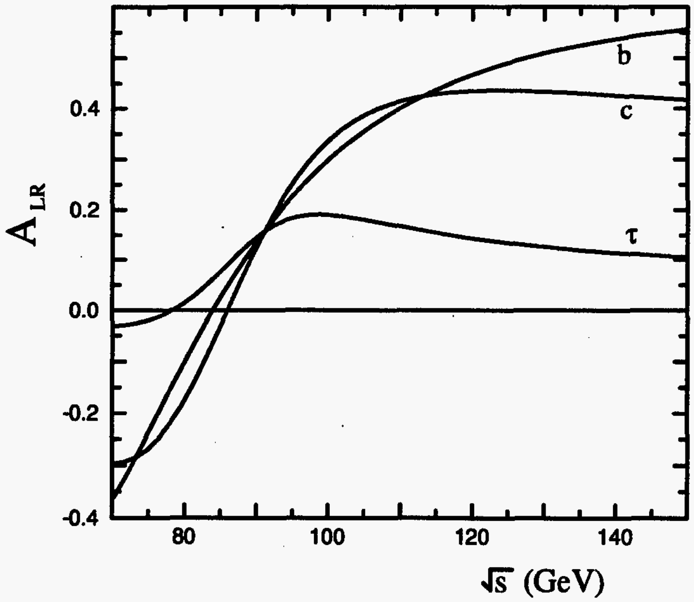

FIGURE 2. Left-right asymmetry for $\mu^-\mu^+ \to f\bar{f}$.

Realistic cuts, efficiencies, systematic errors etc, will not be considered. They are likely to dilute the $b\bar{b}$ and $c\bar{c}$ event rates by a factor of 0.5. In addition, we ignore the radiative Z production tail under the assumption such events are vetoed.

- The (unpolarized) forward-backward asymmetries are illustrated in Fig. 1. Note that A_{FB} is large (near maximal) for $\tau\bar{\tau}$ and $c\bar{c}$ in the region of interest. As we shall see, that feature can help in discriminating signal from background.
- In principle, large polarization in both beams can be important for enhancing "discovery" and precision measurement sensitivity for the Higgs. From Eq. (1), we find for fixed luminosity that $N_S/\sqrt{N_B}$ is enhanced (for integrated signal and background) by the factor

$$\kappa_{\rm pol} = \frac{1 + P_+P_-}{\sqrt{1 - P_+P_- + (P_+ - P_-)A_{LR}}}\,, \tag{8}$$

where the A_{LR} are shown in Fig. 2. That result generalizes the

$P_+ = P_-$ case [5]. For natural beam polarization [1], $P_+ = P_- = 0.2$ (assuming spin rotation of one beam), the enhancement factor is only 1.06. For larger polarization, $P_+ = P_- = 0.5$, one obtains a 1.44 enhancement factor (statistically equivalent to about a factor of 2 luminosity increase). Similarly, $P_+ = P_- = 0.7$ leads to a factor of 2 enhancement or equivalently a factor of 4 scan time reduction. Unfortunately, obtaining even 0.5 polarization simply by muon energy cuts reduces each beam intensity [1] by a factor of 1/4, resulting in a luminosity reduction by 1/16. Such a tradeoff is clearly unacceptable. Polarization will be a useful tool in Higgs resonance "discovery" and studies only if high polarization is achievable with little luminosity loss. Ideas for increasing the polarization are still being explored [1,6]. Tau final state polarizations can also be used to help improve the $H \to \tau\bar{\tau}$ measurement.

- Some "discovery" or sensitivity enhancement can also be obtained from angular discrimination. A proper study would include detector acceptance cuts and maximum likelihood fits. Here, we wish to only approximate the gain. For that purpose, we assume perfect (infinitesimal) binning and obtain a (maximal) measurement sensitivity enhancement factor

$$\frac{1}{2}(1 + P_+P_-)\sqrt{N_S + N_B}\left[\int \frac{dx}{dN/dx}\right]^{1/2}, \tag{9}$$

which becomes, from Equations (1) and (8),

$$\kappa_{\rm pol}\sqrt{\frac{2}{3}}\sqrt{\frac{N_S + N_B}{N_B}}\left(\frac{\tan^{-1}\left(\frac{2}{\zeta}\sqrt{1 - \frac{16}{9}A_{eff}^2 + \zeta}\right)}{\sqrt{1 - \frac{16}{9}A_{eff}^2 + \zeta}}\right)^{1/2}, \quad \zeta \equiv \frac{4}{3}\frac{N_S}{N_B}\frac{\kappa_{\rm pol}^2}{1 + P_+P_-}. \tag{10}$$

- In the case of "discovery", high polarization and/or a near maximal forward-backward asymmetry can significantly reduce the scan time. Additional analysis and detail will be given in [7].

Conclusion

We conclude that $\mathcal{L}_{\rm ave} \simeq 5 \times 10^{30}{\rm cm}^{-2}$ is too low and at least an additional order of magnitude increase in luminosity is needed for the Higgs resonance studies at the First Muon Collider. A factor of 10 in luminosity reduces the scan time by a factor of 10 and increases the resolution by about a factor of 3. The choice of energy and luminosity depends on 1) the scan time needed and 2) how precise a measurement is needed to do physics. For example, to measure $c\bar{c}$, a factor of 10 increase in luminosity provides the improvement from 42% , (Table 1) to about 13% (Table 2), and reduces the scan time from 3 years to over 3 months. Other decays such as WW^* and ZZ^* are very small for this mass regions and to measure them need to improve precision, thus the need for increase in Luminosity, etc.

We have shown that polarization is potentially useful for Higgs resonance studies, but only if the accompanying luminosity reduction is not significant. Large forward-backward asymmetries can also be used to enhance the Higgs "discovery" signal or improve precision measurements, particularly for $\tau\bar{\tau}$. However, to make the s-channel Higgs "factory" a compelling facility, we must attain a very good beam resolution and the highest luminosity possible. An additional "discovery" or sensitivity enhancement can be obtained from angular discrimination. For additional discussion see [7].

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